

The Sound of the Little Bangs

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Data from ultrarelativistic heavy-ions collisions show evidence for temperature-fluctuations on the freeze-out surface of the expanding fireball. These may be remnants of density inhomogeneities in the initial collision overlap region. We present a power-spectrum analysis for heavy-ion collisions analogous to the analysis of the cosmic microwave background radiation. We use a Glauber model for eccentricity to extract the transfer-function needed to produce the observed spectrum and discuss its relation to the mean-free-path of the matter created in the collisions.

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A commonly quoted goal of the heavy-ion programs at Brookhaven Lab (BNL) and CERN, is to recreate conditions similar to those shortly after the Big Bang when the universe was filled with a quark-gluon plasma (QGP). QGP can be created by smashing heavy nuclei together at relativistic speeds in collisions called "little bangs". In the past few decades many theoretical and experimental advances have been made in the study of heavy-ion collisions. Comparisons to the early universe, however, have been scarce [1, 2]. In this paper we explore an analogy between heavy-ion collisions and Big Bang cosmology. Using the heavy-ion equivalent of the map of the cosmic microwave background radiation (CMB), we determine the power-spectrum for the little bangs and we estimate the *transfer-function* necessary to produce the spectrum from the initial conditions.

The hot fireball created in little bangs rapidly expands and cools and when cold enough forms hadrons. Eventually, the system spreads out enough that hadrons stop interacting. This is called the surface of last scattering or freeze-out. The particles then free-stream to the detectors. From measurements of the number, mass, and momentum of these particles, we must infer the properties of the matter that emitted them and extract the essential physics of the QGP. One of the most important discoveries at the Relativistic Heavy Ion Collider (RHIC) at BNL is that the tiny speck of QGP matter produced in the little bangs behaves much like a liquid [3]. This finding is based on the observation that the spatial asymmetries in the initial overlap zone show up as asymmetries in the momentum distributions of final state particles. The observed anisotropy is typically represented by the second Fourier component (v_2) of the azimuthal distribution of observed particles relative to the reaction-plane [4]. v_2 most strongly reflects the almond shape of the initial nuclear overlap region for non central collisions. The magnitude of v_2 can be described surprisingly well with ideal relativistic hydrodynamic models suggesting a liquid-like behavior with minimal viscosity. The

success of these models seems to indicate that the mean-free-path of interactions for the systems constituents is significantly smaller than the size of the system.

Experiments at RHIC have also discovered correlations between particles that extend over a broad range in the longitudinal direction but are narrow in the azimuthal (transverse) direction forming a ridge [5]. A number of different scenarios have been proposed to explain the ridge [6–13]. These include minimum-bias (soft) jets in Au+Au collisions [6], soft gluons radiated by hard partons traversing the overlap region [7], beam-jets boosted by the radial expansion [8], viscous broadening [9], and flux-tube like structures boosted by the radial expansion [11, 12]. The extent of the correlation in the longitudinal direction requires by causality that it must be established very early in the collisions [12]. One of us (PS) proposed that the correlation structures may be understood in terms of fluctuations of higher Fourier components of v_n , particularly $\sqrt{\langle v_3^2 \rangle}$, that arise from anisotropies in the initial energy density converted into momentum space during the expansion [13]. It was subsequently shown with the NEXSPHERIO hydrodynamic model, that indeed, lumpy initial conditions lead to structures similar to those observed in the two-particle correlation measurements [14]. Alver and Roland [15] used the RQMD model to show that lumpiness in the initial collision geometry can lead to a $\sqrt{\langle v_3^2 \rangle}$ in the azimuthal particle production. Petersen *et al.* [16] carried out a similar analysis using an event-by-event hydrodynamic model.

An analogy between the expansion of heavy-ion collisions starting from a lumpy initial energy density and the expansion of the universe starting with quantum fluctuations stretched to cosmological sizes was first pointed out by Mishra *et al.* [2]. They also proposed that the RMS values of v_n ($\sqrt{\langle v_n^2 \rangle}$) could be measured in heavy ion collisions analogous to the power-spectrum extracted from the CMB. They didn't however make a connection between $\sqrt{\langle v_n^2 \rangle}$ and the already existing two-particle correlation measurements. In this work we use transverse

momentum (p_T) correlations published by the STAR collaboration [17] to extract the power-spectrum for heavy-ion collisions. Since the p_T spectra reflects the temperature, p_T correlations are sensitive to local temperature fluctuations. These measurements are directly analogous therefore, to the maps of the CMB. We use a Monte Carlo Glauber model [18] for initial eccentricities to extract the transfer-function required to convert the initial coordinate-space anisotropy into the anisotropy seen in momentum-space. This analysis facilitates a more direct comparison between relativistic heavy-ion collisions and the early universe.

Analogy with Big Bang Cosmology: Measurements of the CMB reveal temperature fluctuations corresponding to over- or under-densities present at the surface of last scattering at about 300,000 years after the Big Bang [19]. These density fluctuations ultimately explain the structure in our universe (Fig. 1 left). Just as quantum fluctuations stretched to cosmic sizes by inflation show up in the CMB, we expect fluctuations from the beginning of the little bangs to show up in heavy-ion data (Fig. 1 right). Measuring temperature-fluctuations in the CMB required precise measurements at more than two million points in the sky. Enough photons are detected at each point to reconstruct the black-body spectrum from which the temperature is determined. In a heavy-ion collision, a few thousand particles are created at most, so a similar map cannot be made for each collision. But whereas we only observe one universe, billions of collisions are created in the lab. By studying p_T correlation data (sensitive to local changes in the p_T -spectra and thus the temperature) accumulated from millions of these collisions, we can search for evidence of hotspots on the surface of last scattering.

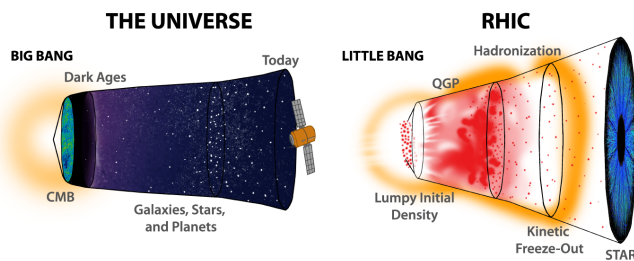


FIG. 1: Schematic of the expansion of the universe after the Big Bang (left) and the expansion of a fireball after little bangs (right). The illustration is by Alexander Doig.

Survival of Density Fluctuations and Various Scales: In Fig. 2 we show the temperature fluctuations calculated from a heavy-ion event generator near the beginning of the expansion and 4 fm/c later. We determined these temperature profiles in the transverse plane at mid-rapidity by translating the energy-density profiles of Werner *et al.* [20] into temperature, using the

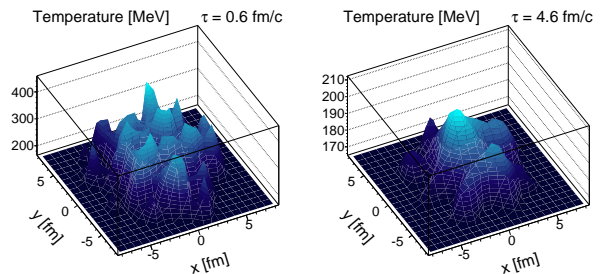


FIG. 2: Temperature profile in the transverse plane for mid-rapidity at proper time $\tau = 0.6$ (left) and 4.6 fm/c (right).

parametrized lattice QCD results for energy-density vs temperature from [21]. The simulations indicate that collisions of Au nuclei (12 fm across), may contain hotspots of size $l_{spot} \approx 1.5$ fm and that remnants of those hotspots persists during the collisions evolution. We also consider the lengths of the acoustic horizon H and the mean-free-path l_{mfp} of the systems constituents to be important.

The acoustic horizon defines how far mechanical information can have propagated through the medium at time τ : $H(\tau) = \int_0^{\tau} c_s(\tau) d\tau$, where τ_{fo} is the freeze-out time. This relates to the growth rate of l_{spot} . We determined $H(\tau)$ from lattice data on the speed of sound (c_s) vs energy density [22] and a hydrodynamic model to specify the energy density vs τ [23]. Fig. 3 shows the acoustic horizon for QCD matter. The phase-transition from QGP to hadron-gas can be seen as a flattening in the slope of H at $\tau \approx 10$ fm/c when H is about 5 fm. The acoustic horizon also dominates the time dependence of the sound that an observer inside the medium would hear (see [24] and [25]). The sound at freeze-out is composed of a superposition of different waves with different frequencies that can be determined from the two-particle momentum correlation data. The horizon defines when frequencies can be heard: Only after half a wavelength fits inside the horizon would that wavelength become "audible". This is the same effect that leads to the lack of large scale fluctuations in the CMB.

The fact that hydrodynamic models do a reasonable job of predicting the value of v_2 suggests that l_{mfp} can be considered small compared to the size of the system. By examining the power-spectrum of heavy-ion collisions which includes information for all values of n (beyond just $n = 2$ or $n = 3$), we hope to better constrain l_{mfp} . As we increase n , we reduce the length scale probed. We only expect an efficient conversion of coordinate-space anisotropies into momentum space when $l_{mfp} \ll 2\pi\langle R \rangle/n$ where $\langle R \rangle$ is the average radius of the systems constituents [26].

Power-Spectrum and Transfer-Function: We determine the power-spectrum from two-particle momentum correlations (related to $(p_{t1} - \langle p_t \rangle)(p_{t2} - \langle p_t \rangle)$) vs the relative azimuthal angles between the particles $\Delta\phi$ [17].

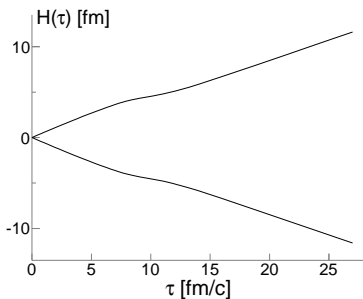


FIG. 3: The acoustic horizon for heavy ion collisions at RHIC.

A narrow peak positioned around small angle separation is observed in the data. This tells us that if a particle comes out with above average p_T , then the nearby particles also tend to have large p_T . This is consistent with expectations from hotspots on the surface of last scattering. The correlation of these fast particles suggests that they are born out of the same high-density, high-temperature lump. We will not attempt to decompose the correlation into different components, i.e. jets and resonances and background. The power-spectrum we extract from data should and does contain all these contributions. We argue that jets do not dominate the observed correlation because the correlations are too large in magnitude, too narrow in ϕ , and too broad in η : there will likely be some contribution but it is suppressed by $1/\text{multiplicity}$). As for resonances, if a hotspot is there, it will emit massive and/or high momentum particles. The decay of a hotspot can proceed through decays into resonances. The power-spectrum reflects all these contributions. Our interpretation of the correlations data in terms of hotspots is supported by several pieces of ancillary evidence. 1) v_n -fluctuations are close to what we expect from density fluctuations from several models and the two-particle correlations data also match what we expect from these models [14–16, 27]. This gives us confidence that the correlations are dominated by the over- and under-densities at the start of the expansion phase. 2) An improved description of particle p_T spectra is obtained when temperature fluctuations are considered [28].

The p_T correlations vs relative angles between the emitted particles ($\Delta\phi$ and $\Delta\eta$) where parametrized in the STAR paper [17]. To extract the power-spectrum, we use that parametrization with $\Delta\eta = 0$ and Fourier-transform the correlation function versus $\Delta\phi$. The coefficients

$$a_n = \frac{2}{\pi} \int_0^\infty f(\Delta\phi) \cos(n\Delta\phi) d(\Delta\phi). \quad (1)$$

vs harmonic n make up the power-spectrum. If we had used number correlations instead of p_T correlations $a_n \approx v_n^2$ [29]. The power-spectrum for little bangs is shown in Figure 4 (left).

Having extracted the power-spectrum from the az-

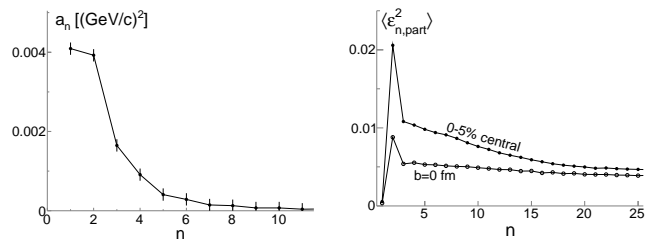


FIG. 4: Left: The power-spectrum versus harmonic number at central rapidity. Right: Participant eccentricity for arbitrary harmonic n for either perfectly central Au+Au collisions or the 5% most central. The intrinsic deformation of the Au nucleus is included.

imuthal correlations of observed particles, we can compare that to the azimuthal distribution of matter in the initial overlap zone. This is calculated using the participant eccentricity ($\epsilon_{n,part}$) for all harmonics n as in Ref. [15]. The fluctuations in the initial geometry cause the major axis of the eccentricity to fluctuate away from the reaction-plane direction. $\epsilon_{n,part}$ is the eccentricity calculated along the major-axis. Fig. 4 (right) shows $\langle \epsilon_{n,part}^2 \rangle$ from a Monte Carlo Glauber model [18] for perfectly central collision ($b=0$ fm) and for the 5% most central collisions. The large $n = 2$ term persists even for central collisions because we include the intrinsic deformation of the Au nucleus in our Monte Carlo. The $n = 1$ term is small because the participants are re-centered so that $\langle x \rangle = \langle y \rangle = 0$. For $b = 0$ collisions we note that the eccentricity is nearly independent of n for $n > 2$. This is because for symmetric collisions and point-like participants, ϵ_{part} depends only on the number of participants, independent of n [30]. In this case, if all harmonics were converted into momentum space equally well, the final correlation function tend to a Dirac delta function at $\Delta\phi = 0$. We expect however, that the conversion of higher harmonic eccentricity will be damped due to the existence of the length scale l_{mfp} . The conversion will be efficient only when $l_{mfp} < 2\pi\langle R \rangle/n$. We can investigate the damping of the higher modes by plotting the transfer-function which is the ratio of the power-spectrum in Fig. 4 (left) to $\langle \epsilon_{part,n}^2 \rangle$ in Fig. 4 (right).

Fig. 5 shows the transfer-function $a_n / \langle \epsilon_{part,n}^2 \rangle$. We use $\langle \epsilon_{part,n}^2 \rangle$ for a centrality range that matches the data. Understanding the shape of the transfer-function implies that one can understand the shape of the correlations data. The transfer-function shows that as n increases, the efficiency for converting coordinate-space anisotropy into momentum space quickly drops off as expected from the condition that the transfer-function should go to zero when $l_{mfp} \sim 2\pi\langle R \rangle/n$. We can make a crude estimate for l_{mfp} based on the transfer-function. If we take $\langle R \rangle = 3$ fm for the average radial position of a participant, and $n = 5$ as the harmonic beyond which the conversion is inefficient, then we get $l_{mfp} \approx 3.5$ fm. This estimate

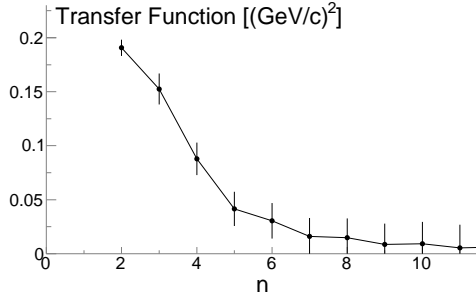


FIG. 5: The transfer-function for central Au+Au collisions extracted from p_T correlations for $n > 1$.

corresponds to a viscosity five times larger than estimates based on the centrality dependence of v_2 [31]. Our crude estimate, however, is geometry based, not accounting for the various phases of the expansion. The authors of Ref. [32] estimate the viscosity from the longitudinal width of the near-side peak in p_T correlations, while our estimate of l_{mfp} is based on the transverse width. The transfer-function should be compared to a more complete model of heavy-ion collisions in order to understand the effects of the expansion velocity, viscosity in the QGP, and viscosity in the hadronic phase.

In this letter we considered the acoustics of heavy ion collisions and discussed the analogy with the early universe. We presented the power-spectrum from heavy ion collisions and derived the transfer-function needed to convert spatial correlations from the initial conditions into the p_T correlations measured at RHIC. We find the transfer-function required to describe the RHIC data can be easily understood in terms of an inefficiency in conversion of coordinate space anisotropy into momentum space when $l_{mfp} > 2\pi\langle R \rangle/n$. We used this transfer-function to make a rough estimate of the mean-free-path of the systems constituents. This approach represents a new method for determining the characteristics of heavy-ion collisions and the QGP and should be further investigated.

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